# ENHANCED NUCLEATE BOILING IN MICROCHANNELS

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## ABSTRACT

This paper studies the nucleate boiling conditions and mechanisms in plasma etched silicon microchannels below 150 µm hydraulic diameter. Boiling regimes and the wall superheat in microchannels with various DI water surface tensions and wall surface roughness are discussed. The experiments show that wall superheat in microchannels is primarily due to the lack of active nucleation sites rather than limited channel space or a high liquid surface tension. By creating small cavities in the channel walls, superheat can be eliminated from as small as 28 µm hydraulic diameter silicon channels.

## INTRODUCTION

The two-phase microchannel heat exchanger is one of the most promising methods for new generation high power IC cooling because it removes large amounts of power without significantly increasing the wall temperature. However, it has been reported that the boiling regimes in microchannels can be quite different from those in larger channels [1-4]. Specifically, due to the small dimensions, large amounts of wall superheat can occur before the onset of boiling. Hypotheses such as "critical bubble size" and "evaporating space" [1] have been proposed to explain the unusual superheat; however, they were not very well supported by various experimental results [2-4].

In phase-change theories [5], liquid vaporization begins with an embryo in the liquid and as long as the embryo is larger than a critical size, a vapor bubble will form. The critical size is determined by the liquid surface tension, degree of superheat, and the ambient pressure, etc. The value of the size can range from a few nanometers to micrometers. If the vapor embryo completely forms within a superheated liquid, it is called "homogeneous nucleation", which is usually associated with high degrees of superheat and extremely rapid rates of vapor generation. Even vapor explosions may occur in some instances. On the other hand, if the vapor embryo forms at the interface between a superheated liquid and another phase, usually solid or gas, it is called "heterogeneous nucleation". The so-called nucleate boiling in the phase change refers to heterogeneous nucleation. Due to the presence of trapped gas in crevices and scratches on the solid surface, the degrees of superheat is much lower because vaporization at a liquid-gas interface can occur at relatively low temperatures.

In our previous study [4], two-phase flow patterns have been visualized in plasma etched silicon channels with 28-171 µm hydraulic diameters. The phase change in channels larger than 100 µm diameter begins with bubble growth on the side walls and annular flow will develop at higher heat fluxes. In channels smaller than 50 µm, however, the phase change begins with a sudden eruption of vapor and mist flow develops immediately. Comparing the results with the nucleation theories, the bubble nucleation mechanism observed in larger channels is heterogeneous nucleation, while the vapor eruption in smaller channels is either heterogeneous nucleation at a smooth surface, or even homogeneous nucleation.

In order to further explore the reasons for the difference in the boiling mechanisms, silicon channels with various surface roughness have been fabricated and the surface tension of DI water is changed to study how these factors affect the phase change in microchannels.

## DESIGN AND FABRICATION

Single test channels with integrated resistive thermometers and aluminum heaters have been previously developed to carry out experiments on two-phase flow regimes and heat transfer measurements [3-4]. These samples allow to locally deposit heat into the plasma-etched, rectangular microchannel and to measure one-dimensional wall temperature distributions simultaneously. Fig. 1 shows the schematic of the instrumented test channel.

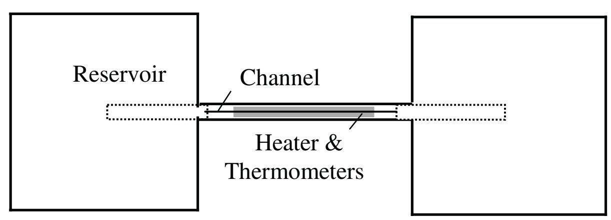



*Fig. 1 Schematic of the single channel test chip with an integrated aluminum heater and seven doped silicon thermometers.*

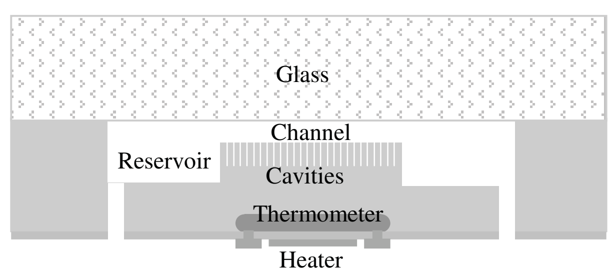
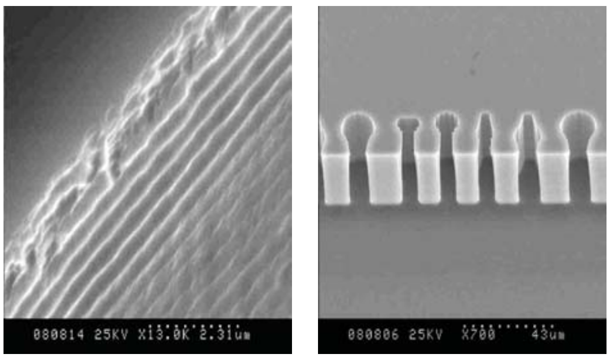



*Fig. 2 Cross sectional view of the test channel. Varying surface roughness of the channels are achieved by either changing plasma etch parameters, or creating 20 µm notches and 150-250 µm deep cavities in the channel walls.*

Fig. 2 is the cross sectional view of the bonded silicon channel with a glass cover piece. The detailed fabrication process is given in [4]. Varying etch parameters were used to achieve different surface roughness for flat-wall channels. Enhanced-wall channels with notches and cavities in the walls were also fabricated, as shown in Fig. 3. These added features in the enhanced walls are designed to trap air and become active nucleation sites as enhanced boiling techniques used in phase change equipment in industrial applications [6]. The notches are formed together with the test channel. The 4-8 μm diameter cavities in the bottom wall are etched together with the reservoirs prior to forming the channels. Because of the small area, the etch rate of the cavities is expected to be slower than that of the larger reservoirs. The estimated depth is 150-250 μm.



*(a)* *(b)*

*Fig. 3 SEM images of plasma etched silicon walls. (a) Side wall roughness from standard etch program. (b) Notches on the side wall. The notches are 20 μm deep into the wall, with 4 μm openings to the channel.*

*Table 1 Structural parameters*

| Structure | Dimension |
|---|---|
| Reservoirs | 600 μm wide, 250 μm deep, 1 cm long |
| Freestanding beam | 1.3 mm wide, 2 cm long |
| Channel dimensions | 10-150 μm wide, 10-200 μm deep, 2 cm long |
| Side wall notches | 4 μm wide opening, 10 μm deep |
| Bottom cavities | 4-8 μm diameter, 100-200 μm deep |
| Si substrate thickness | 480 μm |
| Glass thickness | 520 μm |

The overall size of the test chip is 6.5 cm long and 2 cm long. Table 1 lists the detailed structural parameters of the test devices.

## PHASE CHANGE IN FLAT-WALL CHANNELS

The difference in boiling regimes in channels larger than 100 μm diameter and channels smaller than 50 μm diameter has been visualized in previous study [4]. In order to study how the wall superheat is related to the boiling mechanisms, same channels were used to make the temperature profile measurement, a 113 μm diameter channel and a 44 μm diameter channel.

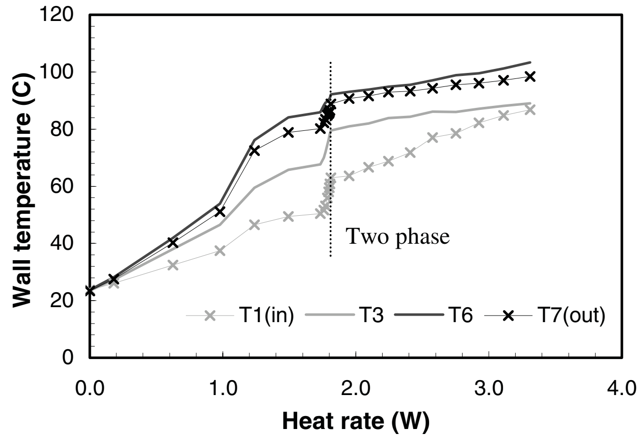



*Fig. 4 Wall temperature change as a function of input heat rate in a 100 μm wide, 130 μm deep, 113 μm hydraulic diameter channel with flat walls at 0.1 ml/min DI water flow rate.*

Fig. 4 shows the wall temperature change against heat rate in a 113 μm diameter channel. The previous phase change visualization [4] shows that the boiling initiates from small bubble growth in the channel, and the annular flow regime is the dominant flow pattern. From the boiling curves, the initial bubble nucleation, also called "partial boiling", causes a small plateau because the bubble departure induces annular flows in the channel, which increase the heat transfer coefficient, but not as high as in the two-phase region. When the boiling begins, the two-phase annular flow dominates in the channel, yielding a very high heat transfer coefficient; hence a second plateau results. Just as nucleation in large pools, the gas bubbles form below the boiling temperature due to lower gas solubility, and they turn to vapor cores later when the temperature is high enough. Therefore, the wall superheat before the onset of boiling is below 5 °C.

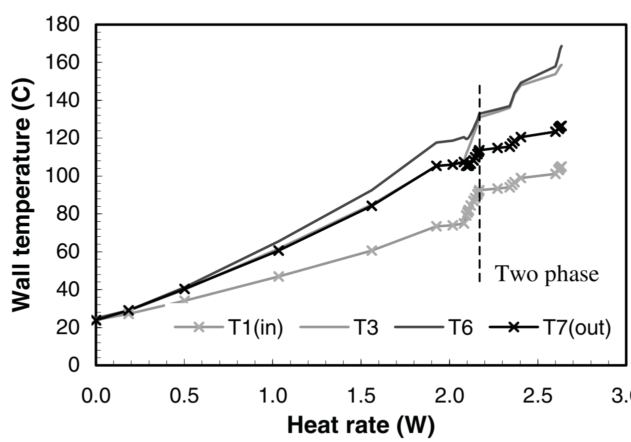



*Fig. 5 Wall temperature change as a function of input heat rate in a 50 μm wide, 40 μm deep, 44 μm hydraulic diameter channel with flat walls at 0.02 ml/min DI water flow rate.*

Fig. 5 gives the wall temperature change against heat rate in a 44 μm diameter channel. Just as the clear difference in the boiling mechanisms, the boiling curves in the two typical channels are also different. The 44 μm channel shows an eruption of vapor with more than 20 °C wall superheat before the onset of boiling. There is no clear plateau in the two-phase region, indicating that mist flow forms immediately as the result of phase change. Because the mist flow has much lower heat transfer coefficients than those of the annular flow, the wall temperatures keep rising with increasing input heat rate.

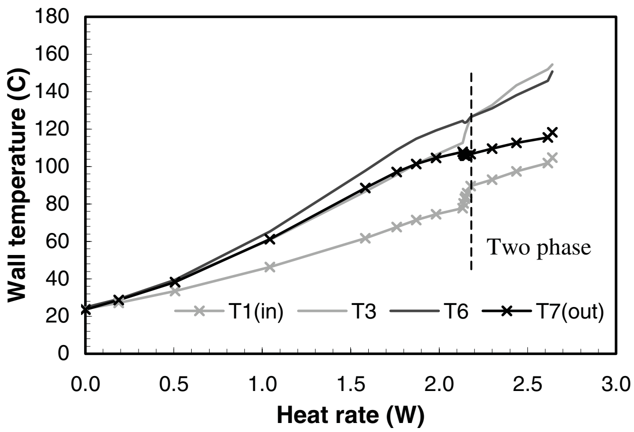



*Fig. 6 Wall temperature changes as a function of heat rate in a 50 μm wide, 40 μm deep, 44 μm hydraulic diameter channel with flat walls at 0.02 ml/min flow rate of 200 ppm TritonX-100 DI water solution.*

In order to study how surface tension affects the nucleation mechanisms in microchannels, surfactant is added to DI water to lower its surface tension. TritonX-100 and DI water solutions with three concentrations have been used in the 44 μm channel in the wall temperature superheat experiments. Fig. 6 is the wall temperature measurement with 200 ppm TritonX-100 solution, indicating about the same amount of wall superheat as in the case of pure DI water. Eruption boiling mechanisms were also observed. Further experiments with 2000 ppm and 10000 ppm solutions have similar boiling curves as in Fig. 6, within 4 °C temperature difference. Therefore, the nearly 20 °C wall superheat is not directly related to a high surface tension.

## PHASE CHANGE IN ENHANCED-WALL CHANNELS

Four channels with enhanced walls and hydraulic diameters ranging from 28-73 μm have been tested with pure DI water. Nucleate boiling has been observed in all the channels with less than 5 °C superheat before the onset of boiling, and the bubble nucleation induced annular flow was first observed in below 100 μm diameter channels.

Fig. 7 is the image of bubble formation and growth from the bottom cavities in a 72.5 μm diameter channel. The bubble growth and departure cycles are exactly the same as what have been observed in larger flat wall channels; while the number of nucleation size is significantly increased due to the large number of cavities in the bottom.

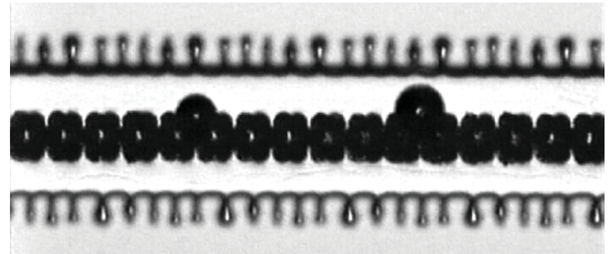


*Fig. 7 Bubble nucleation from cavities in the bottom of a 120 μm wide, 52 μm deep, 72.5 μm hydraulic diameter channel.*

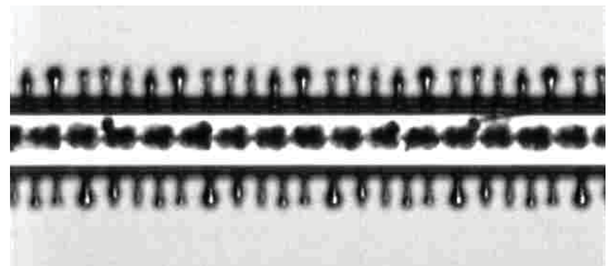


*Fig. 8 Annular flow in a 74 μm wide, 52 μm deep, 61 μm hydraulic diameter channel at 0.1 ml/min DI water flow rate.*

An annular flow pattern is shown in Fig. 8, which has never been observed in flat-wall channels below 100 μm. The annular flow forms when there is enough number of nucleation sites and the bubble generation frequency is high enough, thus a continuous thin water film covers the entire channel wall.

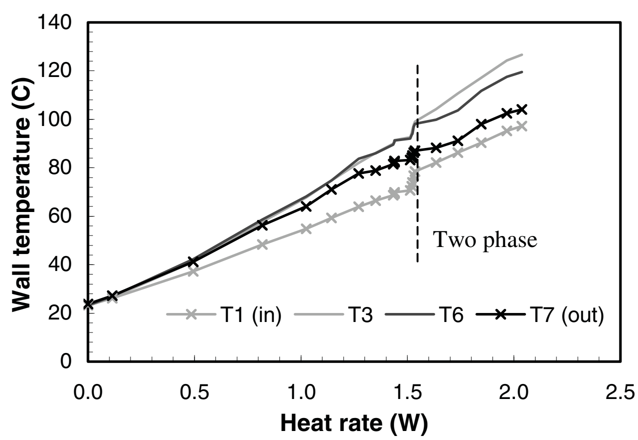



*Fig. 9 Wall temperature change as a function of the heat rate in 50 μm wide, 44 μm deep, 47 μm hydraulic diameter channel with enhanced walls at 0.02 ml/min DI water flow rate.*

The wall temperature measurements provide the information on the wall superheat. Fig. 9 shows the wall temperature change against heat rate in a 47 μm diameter channel at 0.02 ml/min constant DI water flow rate. Although steady annular flow was not observed in this channel, the wall superheat before the onset of boiling is significantly reduced, compared with the results in flat wall channels with similar dimensions in Figs. 5 and 6. The small flat before the onset of boiling is the result of partial boiling. Due to the small dimensions and relatively large heat rate increment, the annular flow quickly turns into mist flow after the onset of boiling; hence the expected plateau does not appear on the boiling curves. However, it can be made possible in heat exchangers with a large number of channels and lower distributed heat fluxes.

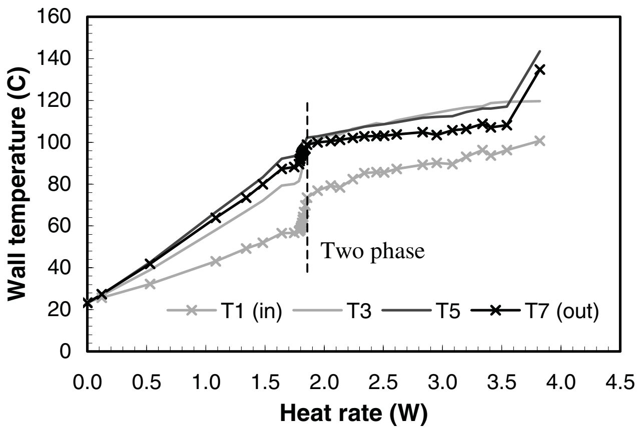



*Fig. 10 Wall temperature change in a 120 µm wide, 52 µm deep, 72.5 µm diameter channel with enhanced walls at 0.1 ml/min DI water flow rate.*

Fig. 10 is the boiling curves from a 72.5 µm diameter channel at 0.1 ml/min constant DI water flow rate. Again, the bubble nucleation has been observed and the onset of boiling occurs within 5 °C wall superheat. Because there were enough nucleation sites in the channel, steady annular flow developed, yielding large heat transfer coefficients and a long plateau in the two-phase flow region.

## DISCUSSION

The experiments with low surface tension liquids do not support the "critical size" hypothesis. In principle, the critical bubble size in homogeneous mechanism can be much smaller than 50 µm. Furthermore, bubble growth from smaller than 10 µm diameter to departure size of 50-100 µm diameter have been visualized in earlier experiments [4], which indicates that the confined space in microchannels is not the reason of the eruption boiling.

In the flat-wall channels, all nucleation sites are on the side walls rather than on the bottom [4]. In the etch process, the alternating etch and passivation cycles leave steps of 0.2-0.4 µm on the side wall, as shown in Fig. 3(a). This leads to the possibility of larger cavities on the side wall is much higher than that of the bottom. Hsu has proposed a model on the dimensions of active nucleation site as a function of wall superheat [7]. The model shows that cavities below 1 µm diameter are not active until significant amounts of wall superheat, indicating that high superheat is possible for flat-wall channels, especially small diameter channels with smaller internal surface area and even less densities of active nucleation sites. This might explain the eruption boiling observed in smaller flat-wall channels.

Further experiments with enhanced-wall channels prove that gas-trapping cavities help to initiate the phase change regardless of the channel dimensions. On the other hand, however, the 20 µm notches do not actively become nucleation sites. A possible reason is that the native oxide film on the silicon surface makes it hydrophilic, which improves the wetting on the surface and decreases the number of active nucleation sites.

## CONCLUSIONS

This study proves that the surface condition of the channel walls plays a key role in determining the nucleation mechanism in microchannels. It has been experimentally proved that the large amount of superheat in smaller than 50 µm diameter flat-wall channels is caused by the low surface roughness. And this unusual superheat can be eliminated with enhanced surface which have gas-trapping cavities that can induce the phase change at very low superheat.

A major size effect for boiling in microchannels is that a single bubble can easily fill the entire channel and induce either annular or mist flow depending on the quality. Hence for the design of two-phase microchannel heat exchangers, the quality must be limited for small channels below 50 µm in hydraulic diameter. Nevertheless, the high superheat nucleation mechanism can be controlled by making cavities in these channels, which proved effective in reducing the superheat level before the onset of boiling.


## ACKNOWLEDGMENTS

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